Biophysical responses near equatorial islands in the Western Pacific Ocean during El Niño/La Niña transitions

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Received 28 August 2013; revised 7 October 2013; accepted 7 October 2013; published 29 October 2013.

[1] The biological response in the western equatorial Pacific Ocean during El Niño/La Niña transitions and the underlying physical mechanisms were investigated. A chlorophyll *a* bloom was observed near the Gilbert Islands during the 2010 El Niño/La Niña transition, whereas no bloom was observed during the 2007 El Niño/La Niña transition. Compared to the previously observed bloom during the 1998 El Niño/La Niña transition, the 2010 bloom was weaker, lagged by 1–2 months, and was displaced eastward by ~200 km. Analysis suggested that the occurrence, magnitude, timing, and spatial pattern of the blooms were controlled by two factors: easterly winds in the western equatorial Pacific during the transition to La Niña and the associated island mass effect that enhanced vertical processes (upwelling and vertical mixing), and the preconditioning of the thermocline depth and barrier layer thickness by the preceding El Niño that regulated the efficiency of the vertical processes. Despite the similar strength of easterly winds in the western equatorial Pacific during the 1998 and 2010 transitions to La Niña, the 2009–2010 El Niño prompted a deeper thermocline and thicker barrier layer than the 1997–1998 El Niño that hampered the efficiency of the vertical processes in supplying nutrients from the thermocline to the euphotic zone, resulting in a weaker bloom. **Citation:** Gierach, M. M., M. Messié, T. Lee, K. B. Karnauskas, and M.-H. Radenac (2013), Biophysical responses near equatorial islands in the Western Pacific Ocean during El Niño/La Niña transitions, *Geophys. Res. Lett.*, *40*, 5473–5479, doi:10.1002/2013GL057828.

1. Introduction

[2] Islands and atolls in the tropics are known to influence biological and physical processes in adjacent waters [e.g., *Heywood et al*., 1990; *Signorini et al*., 1999; *Messié et al*., 2006; *Karnauskas et al*., 2007, 2008, 2013; *Karnauskas and Cohen*, 2012]. A large chlorophyll *a* (chl *a*) bloom was observed to the west of the Gilbert Islands, part of the Republic of Kiribati (i.e., a chain of low-lying atolls and islands in the western equatorial Pacific Ocean located approximately 2°N–2°S, 172°E–176°E), during the 1998 El Niño/La Niña transition [*Murtugudde et al*., 1999; *Wilson and Adamec*, 2001; *Ryan et al*., 2002; *Messié et al*., 2006]. The bloom was attributed to enhanced vertical processes (upwelling and vertical mixing) facilitated by a thinning barrier layer at the base of the mixed layer [*Murtugudde et al*., 1999], the reappearance and shoaling of the Equatorial Undercurrent (EUC) that brought nutrient-rich thermocline waters closer to the base of the mixed layer [*Wilson and Adamec*, 2001], and a combination of both aforementioned processes [*Ryan et al*., 2002]. *Messié et al*. [2006] suggested that the enhanced vertical processes reflected an "island mass effect" (after *Doty and Oguri* [1956]), wherein the Gilbert Islands disrupted local ocean circulation to the west of the island chain generating instabilities (meanders and eddies) that enhanced mixing and shoaling of the EUC. *Messié et al*. [2006] also reported that no chl *a* bloom was observed for two subsequent small El Niño events (i.e., 2002–2003 and 2004–2005) that were not followed by La Niña events. The fact that not all El Niño events are followed by La Niña events led *Kessler* [2002] to question whether the El Niño-Southern Oscillation (ENSO) is inherently a cycle or a series of events.

[3] Since the study by *Messié et al*. [2006], there have been two El Niño events (i.e., 2006–2007 and 2009–2010) that transitioned into La Niña events. To date, there has been no investigation of the necessary physical conditions for a chl *a* bloom to occur. In this study, we report a moderate bloom during the 2010 El Niño/La Niña transition and the lack of a bloom during the 2007 El Niño/La Niña transition. We document the physical ocean state and physical forcing for various El Niño events and discuss the combined effect of ocean preconditioning associated with El Niño and wind forcing associated with the transition to La Niña and the related island mass effect that result in different biological responses.

2. Data

[4] A variety of data products were utilized to analyze differences in physical conditions and biological responses associated with El Niño/La Niña transitions. The 1998, 2007, and 2010 events were investigated, but this study primarily focuses on the 1998 and 2010 El Niño/La Niña transitions as chl *a* blooms were observed in association with these events. Satellite-based products included monthly 1/4° Cross-Calibrated Multi-Platform (CCMP) ocean surface winds

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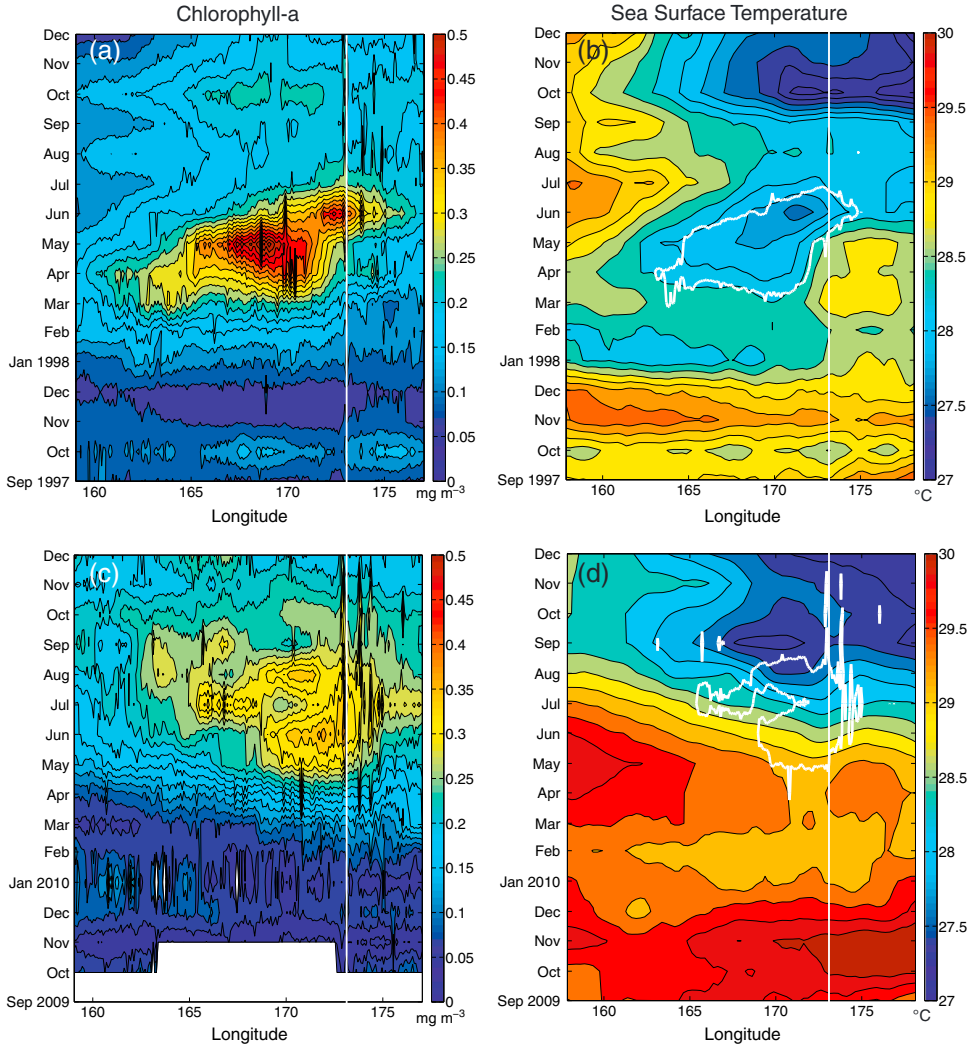

Figure 1. (a, c) 2°N–2°S averaged SeaWiFS chl *a* (mg m^{-3}) and (b, d) SST (°C) from 158°E–178°E for the 1998 El Niño/La Niña transition (Figures 1a and 1b) and the 2010 El Niño/La Niña transition (Figures 1c and 1d). The vertical white lines denote the approximate location of the Gilbert Islands. Black contour intervals are approximately 0.03 mg m^{-3} (Figures 1a and 1c) and 0.3 °C (Figures 1b and 1d). The bloom domain (>0.3 mg m^{-3}) is overlaid in Figures 1b and 1d as a white line.

(http://podaac.jpl.nasa.gov/dataset/CCMP_MEASURES_ATLAS_L4_OW_L3_5A_MONTHLY_WIND_VECTORS_FLK), 5 day 1/3° Ocean Surface Current Analysis Real time (OSCAR; http://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_third-deg), and daily 1/4° Group for High Resolution Sea Surface Temperature (GHRSST) Advanced Very High Resolution Radiometer (AVHRR)-based Optimal Interpolation Sea Surface Temperature (OISST; http://podaac.jpl.nasa.gov/dataset/NCDC-L4LRblend-GLOB-AVHRR_OI) from the Physical Oceanography Distributed Active Archive Center (http://podaac.jpl.nasa.gov/), as well as monthly 9 km Sea-viewing Wide Field-of-view Sensor (SeaWiFS) chl *a* from Ocean Biology Processing Group (http://oceancolor.gsfc.nasa.gov/) and monthly sea level anomalies (SLA) on 1/3° Mercator grids from AVISO (http://www.aviso.oceanobs.com/). In situ products included daily 20°C isotherm depth, subsurface temperature, ADCP current profiles (for the 1998 transition), and fixed depth current data (for the 2010 transition) from the Tropical Atmosphere Ocean (TAO) buoy array provided by the NOAA Pacific Marine Environmental Laboratory (http://www.pmel.noaa.gov/tao/). Daily ADCP current, fixed depth current, and 20°C isotherm depth data, as well as 5 day OSCAR and daily OISST data, were averaged to obtain monthly means.

[5] Monthly 20°C isotherm depth data were used as proxies for the thermocline/nutricline depth. Monthly zonal currents from ADCP and fixed depth current profilers were used as proxies for the EUC, wherein maximum eastward velocities at depth denote the EUC. The EUC serves as an important iron source for the equatorial Pacific.

[6] Monthly 1/2° barrier layer thickness (BLT) data were estimated from the Simple Ocean Data Assimilation (SODA) reanalysis v2.2.4 [*Carton and Giese*, 2008] (http://soda.tamu.edu). BLT was computed as the difference between the isothermal layer (temperature change of 0.2°C with a reference depth of 5 m) and the mixed layer depth (variable density criterion corresponding to a temperature change of 0.2°C at 5 m) [*de Boyer Montégut et al.*, 2004; *Bosc et al.*, 2009]. Results were robust when compared to in situ-derived BLT data (see Figure 7 of *Messié and Chavez* [2013] for a comparison of SODA BLT with *Bosc et al.* [2009]).

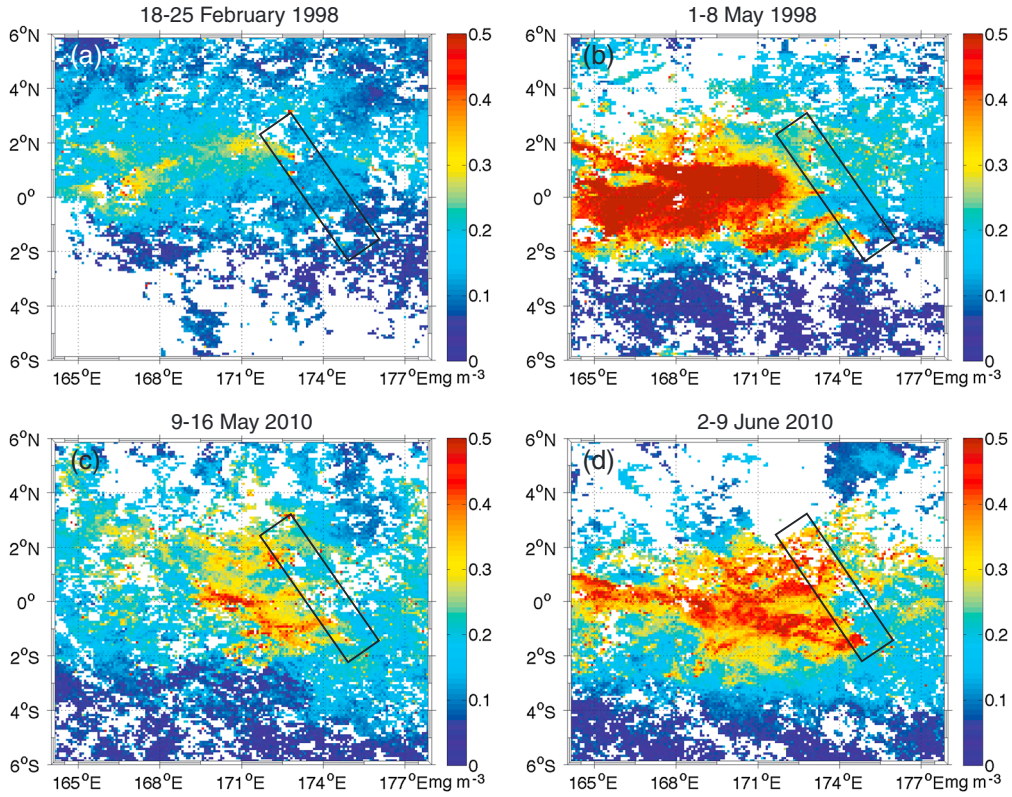

Figure 2. SeaWiFS chl *a* (mg m^{-3}) on (a) 18–25 February 1998, (b) 1–8 May 1998, (c) 9–16 May 2010, and (d) 2–9 June 2010. The black boxes denote the approximate location of the Gilbert Islands. Island mass effects are observed in association with the Gilbert Islands in Figures 2a–2d. White areas denote cloud cover. Note that cloud cover was an issue from March–April 1998, making it difficult to observe island mass effects during that time period.

3. Biophysical Response to El Niño/La Niña Transitions

3.1. Chl *a* Enhancement

[7] Three El Niño/La Niña transitions occurred in the SeaWiFS record (i.e., 1998, 2007, and 2010) based on the Oceanic Niño Index (www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). Increased chl *a* concentrations (>0.3 mg m^{-3}) were observed during the 1998 [*Messié et al.*, 2006] and 2010 El Niño/La Niña transitions (Figures 1a and 1c), whereas there was no significant increase during the 2007 transition (supporting information Figure S1a). A sharp step was observed in the chl *a* response for both transitions (Figures 1a and 1c), as was noted by *Messié et al.* [2006] for the 1998 transition. This pattern is clearly influenced by the presence of the Gilbert Islands with enhanced biological productivity to the west of the islands, as was additionally pointed out in the longer-term average by *Karnauskas and Cohen* [2012]. Figure 2 confirms the occurrence of blooms in association with the Gilbert Islands for the 1998 and 2010 transitions. The location and timing of peak chl *a* concentrations varied between transition events. The 1998 transition approximately began in January 1998 with peak values around 170°E in May 1998 [*Messié et al.*, 2006], whereas the 2010 transition approximately began in March 2010 with peak values around 172°E in June 2010 (Figures 1a and 1c). In addition to a 1–2 month lag and 2° eastward shift in location, the magnitude of peak chl *a* concentrations was also weaker during the 2010 transition.

3.2. Physical Drivers for Chl *a* Enhancement

[8] El Niño events are marked by periods of anomalous westerly winds and eastward currents in the equatorial Pacific with associated changes in subsurface ocean circulation and stratification (e.g., deepened thermocline/nutricline and weakened EUC). Westerly winds and eastward currents were observed in the western equatorial Pacific from September–December 1997 for the 1997–1998 El Niño and September 2009–February 2010 for the 2009–2010 El Niño (Figure 3). Westward currents and easterly winds returned in January 1998 and March 2010. These dates are consistent with the chl *a* response in terms of the 1–2 month lag of the chl *a* bloom in 2010 compared to that in 1998 (Figures 1a and 1c).

[9] Easterly winds were relatively uniform in magnitude during the 1998 transition (Figure 3a). Westward surface currents varied, with the strongest velocities around and to the west of the Gilbert Islands from January–April 1998 (Figure 3b). SLA dropped during this time, consistent with the shoaling of the isotherms in the upper 100 m and the EUC (Figures 1b and 4a–4c). BLT during this period was very thin (a few meters or less) (Figure 4d), which made the vertical exchange of water between the upper mixed layer and the thermocline more efficient for the same wind forcing. The enhanced vertical processes resulted in a decrease of sea surface temperature (SST) (Figure 1b). These physical responses illustrate an island mass effect as discussed by *Messié et al.* [2006], which contributed to a chl *a* bloom to

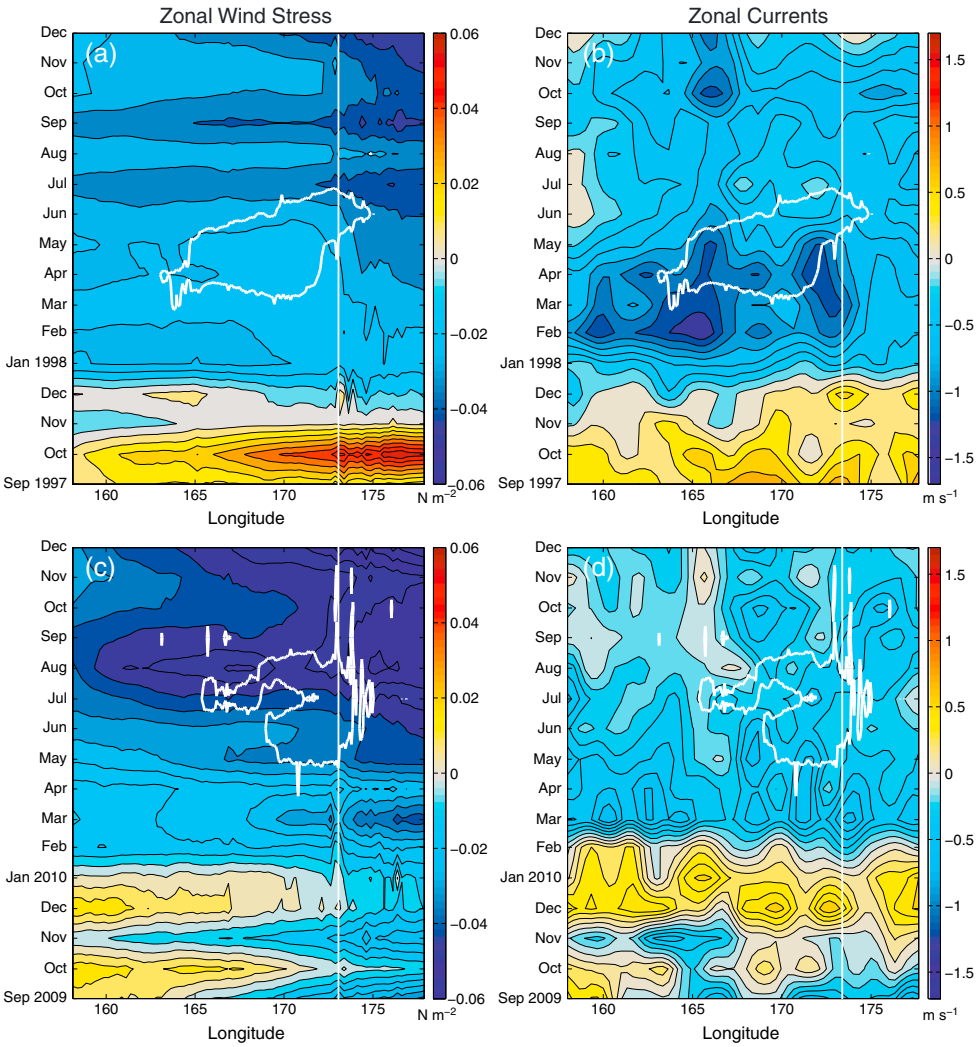

Figure 3. 2°N–2°S averaged (a, c) CCMP zonal wind stress (N m^{-2}) and (b, d) OSCAR zonal currents (m s^{-1}) from 158°E–178°E for the 1998 El Niño/La Niña transition (Figures 3a and 3b) and the 2010 El Niño/La Niña transition (Figures 3c and 3d). The vertical white lines denote the approximate location of the Gilbert Islands. Black contour intervals are approximately 0.01 N m^{-2} (Figures 3a and 3c) and 0.2 m s^{-1} (Figures 3b and 3d). The bloom domain (>0.3 mg m^{-3}) is overlaid in Figures 3a–3d as a white line.

the west of the Gilbert Islands (Figures 1a and 2a–2b) as more nutrients were brought to the euphotic zone via enhanced vertical exchange with the nutrient-rich thermocline waters. The peak of the chl *a* bloom in May 1998 was associated with the surfacing of the EUC (Figures 1a, 2b, and 4a). These results are consistent with those of *Messié et al.* [2006].

[10] During the 2010 El Niño/La Niña transition, a moderate chl *a* bloom was observed in approximately the same location (2° eastward shift) as that during the 1998 El Niño/La Niña transition with a 1–2 month lag (Figures 1c and 2c–2d). In comparison with the physical conditions during the 1998 event, the barrier layer was substantially thicker during the 2010 event (Figures 4d and 4h). This reduced the efficiency of vertical mixing between the mixed layer and the thermocline. Moreover, the thermocline and EUC were much deeper (Figures 4a and 4e). Consistent with this, SLA did not become negative until March–May 2010 (Figure 4f). Even the negative SLA during the peak of the chl *a* bloom was much smaller in magnitude during the 2010 event than the 1998 event (Figures 4b and 4f). The deeper thermocline/EUC and thicker barrier layer impeded the efficiency of the vertical exchange between the upper mixed layer and the thermocline. As a result, the decrease in SST during January–May was smaller during the 2010 event than that during the 1998 event (Figures 1b and 1d). The smaller magnitude of the chl *a* bloom during the 2010 event was a result of less vigorous vertical processes.

[11] The differences in timing and location of the peak chl *a* bloom between the two events were consistent with equatorial zonal wind forcing. Regarding the timing, the transition from westerly to easterly winds occurred in November–December for the 1998 event (Figure 3a) and in January for the 2010 event (Figure 3c), with easterly winds being somewhat stronger in 2010 than 1998. As a result, the shoaling of the EUC during the 2010 transition was delayed, with the shallowest depth of the EUC occurring in June (Figure 4e) as opposed to May in the 1998 transition (Figure 4a). This explains the timing of the peak chl *a* blooms between transition

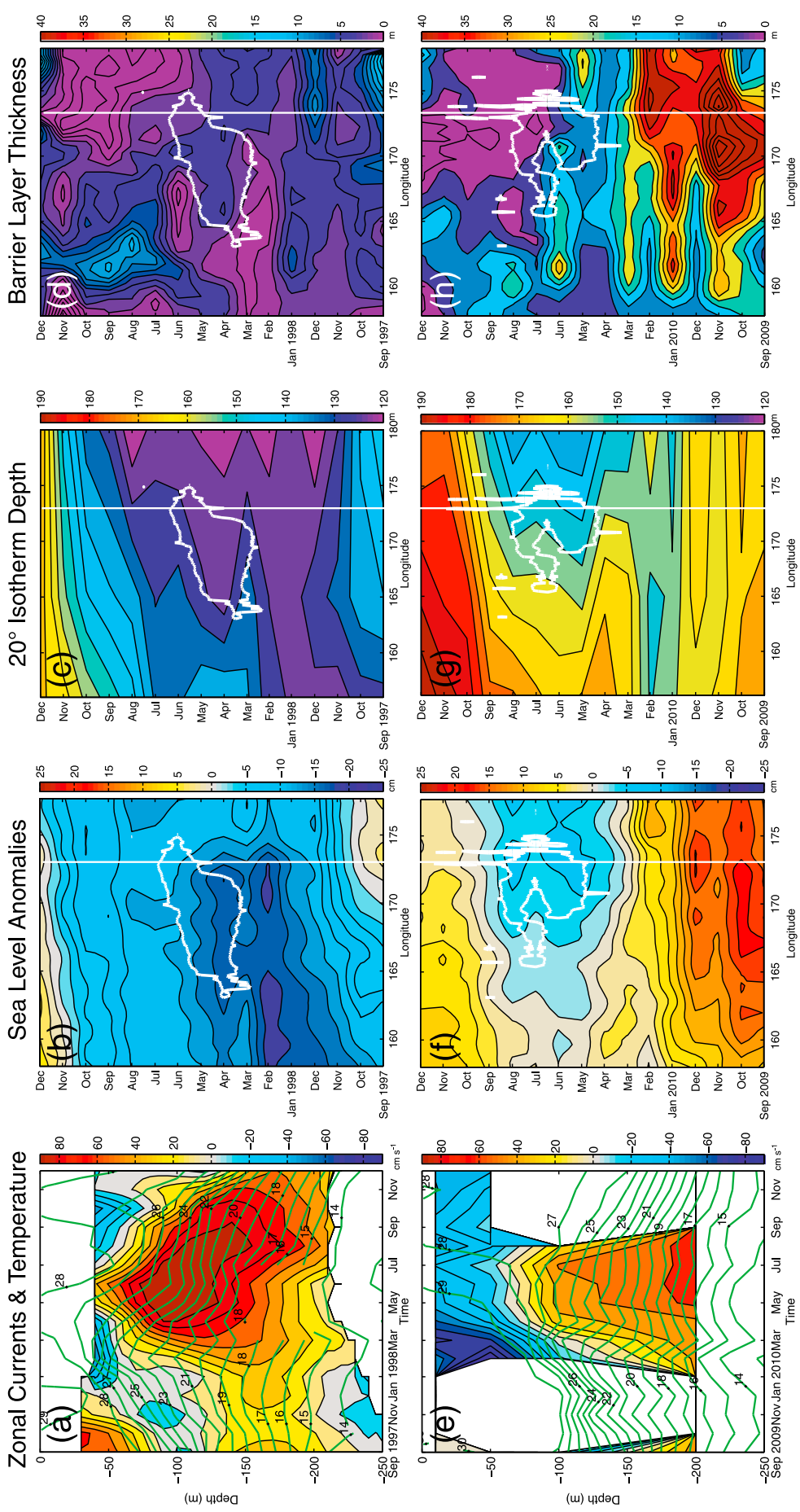

Figure 4. (a, e) Subsurface zonal currents (cm s^{-1}) and temperature (°C; green contours) from the TAO array at 0°N, 165°E, and 2°N–2°S averaged (b, f) SLA (cm), (c, g) TAO array 20° isotherm depth (m), and (d, h) SODA-derived BLT (m) from 158°E–178°E for the 1998 El Niño/La Niña transition (Figure 4a–4d) and the 2010 El Niño/La Niña transition (Figures 4e–4h). ADCP current profiles are used for the 1998 transition and fixed depth current data for the 2010 transition. Note that the 20° isotherm depth is used as a proxy for the thermocline/nutricline depth. White regions or discontinuous lines in Figures 4a and 4e illustrate a lack of available data. The vertical white lines denote the approximate location of the Gilbert Islands. Black contour intervals are approximately 11 cm s^{-1} (Figures 4a and 4e), 2 cm (Figures 4b and 4f), 5 m (Figures 4c and 4g), 1.2 m (Figure 4d), and 5 m (Figure 4h). The bloom domain (>0.3 mg m^{-3}) is overlaid in Figures 4b–4d and 4f–4h as a white line.

events (i.e., May 1998 and June 2010) (Figures 1a and 1c). As for the difference in spatial location, easterly winds in the boreal spring of 2010 were substantially stronger near the Gilbert Islands while those in 1998 were more uniform across the equatorial western Pacific (Figures 3a and 3c). Therefore, the shoaling of the thermocline in 2010 was more confined to the region near the islands while that in 1998 was further west (as seen from the difference in the pattern of negative SLA in Figures 4b and 4f). This explains why the chl *a* bloom during the 2010 transition was centered more to the east (closer to the Gilbert Islands) than that during the 1998 transition (Figures 1a, 1c, 2b, and 2d).

4. Discussion

[12] In summary, the physical mechanisms for observed chl *a* enhancement were similar for the 1998 and 2010 transitions, wherein both were associated with a shoaled EUC that brought nutrient-rich thermocline waters closer to the mixed layer to facilitate vertical exchanges. Nevertheless, the deeper thermocline/EUC and thicker barrier layer in 2010 made the vertical exchange less efficient compared to that in 1998. There are two factors that control the efficiency of the vertical processes and the corresponding chl *a* response: the structure of the preceding El Niño that preconditions the properties of the thermocline and mixed layer (e.g., depth of the thermocline/EUC and BLT), and the strength of the easterly trade winds and the related island mass effect that drive the vertical processes during the transition to La Niña. The latter is quite similar between the boreal spring of 1998 and 2010 west of the Gilbert Islands (Figures 3a and 3c), whereas the preceding ocean state was markedly different during the peak of the 1997–1998 El Niño and 2009–2010 El Niño (Figure 4).

[13] The thermocline and EUC were shallower, and the barrier layer was thinner during the peak of the 1997–1998 El Niño than the 2009–2010 El Niño (Figure 4). In fact, the total decrease in SLA (or uplift of the thermocline) from January–May 1998 and 2010 was similar (Figures 4b and 4f), reflecting the similar magnitude of wind forcing and the associated Ekman pumping (the wind in 1998 was slightly weaker than that in 2010) (Figures 3a and 3c). However, the 2010 event started with a positive SLA (deeper EUC), while the 1998 event started with a negative SLA (shallower EUC). In other words, even though the total shoaling of the thermocline was similar between the two events, the thermocline depth was much deeper during the 2010 transition because of the greater downward perturbation (i.e., greater initial depth) during the peak of the 2009–2010 El Niño, thus resulting in a smaller bloom.

[14] The combined effect of the two factors discussed above (i.e., preconditioning of the thermocline depth by the preceding El Niño and the strength of easterly wind forcing during the transition to La Niña that lifts the thermocline) also explain why there was no significant chl *a* bloom during the 2007 El Niño/La Niña transition (Figure S1). The thermocline depth and SLA to the west of the Gilbert Islands in early 2007 were not as pronounced as that in 1998 and 2010 (Figures S1f, S1g, 4b, 4c, 4f, and 4g). The barrier layer was also thicker in 2007 than that in 1998 (although not as thick as in 2010) (Figures S1h, 4d, and 4h). However, easterly trade winds during the 2007 transition were relatively similar to those in 1998 and 2010 (the wind in 2007 was slightly weaker than that in 2010) (Figures S1c, 3a, and 3c). Consequently, the thermocline and EUC did not shoal as much and there was no negative SLA during spring 2007 (Figures S1 and 4). As a result, no chl *a* bloom was observed.

[15] While equatorial zonal winds during the transition to La Niña determine how much the thermocline/EUC shoals, the structure of the El Niño preconditions the initial thermocline/EUC depth before the transition to La Niña (if any). Since the 1990s, a new flavor of El Niño otherwise known as the dateline El Niño [*Larkin and Harrison*, 2005], El Niño Modoki [*Ashok et al*., 2007], central Pacific (CP) El Niño [*Kao and Yu*, 2009], or warm-pool El Niño [*Kug et al*., 2009] has been reported to occur more frequently than the preceding few decades. This flavor of El Niño has maximum warming in the central equatorial Pacific, in contrast to the classic eastern Pacific (EP) El Niño or cold-tongue El Niño that has maximum warming in the eastern equatorial Pacific. The 1997–1998 and 2009–2010 El Niño events are the largest EP and CP El Niño observed in the past three decades by satellites [*Lee and McPhaden*, 2010]. During the peak of a large EP El Niño, like the 1997–1998 event, substantial weakening of the easterly trade winds cause substantial shoaling of the western Pacific thermocline (corresponding to very negative SLA) (see Figure 1e of *Gierach et al*. [2012]). For CP El Niño events, like the 2009–2010 event, the western Pacific thermocline does not shoal as much (SLA not as negative) (see Figure 1f of *Gierach et al*. [2012]). For small EP El Niño, like the 2006–2007 event, the western Pacific thermocline depth is somewhat similar to that for CP El Niño.

[16] As mentioned previously in section 1, not all El Niño events are followed by La Niña events. The warming associated with weaker CP El Niño events, such as the 2002–2003 and 2004–2005 events, lingers into the boreal spring after the peak of El Niño without a subsequent La Niña. Because the structure of the western Pacific thermocline was not as perturbed by CP El Niño (and small EP El Niño like the 2006–2007 event), it tends to be more difficult for a chl *a* bloom to occur after these small to moderate El Niño events.

[17] The vertical processes discussed above focused on wind-induced upwelling and mechanical mixing, both of which can be diagnosed from the strength of the easterly trade winds. However, there are two other potential factors that could induce vertical mixing. The first potential factor is baroclinic eddies. We examined eddy kinetic energy (EKE) using altimeter data and found significantly larger EKE in the boreal spring of 1998 than that of 2010 that was confined between 172°E–174°E (not shown). This cannot explain the spatial extent of the bloom in 1998 that extended westward to 164°E. The second potential factor is vertical mixing induced by vertical shear. The limited availability of TAO mooring data (especially for vertical shear) poses a difficulty in diagnosing this effect. Its potential contribution needs to be investigated further in future studies.

5. Concluding Remarks

[18] This study investigated the biological response in the western equatorial Pacific Ocean to El Niño/La Niña transitions and explained the responsible physical mechanisms. We reported a chl *a* bloom near the Gilbert Islands associated with the 2010 El Niño/La Niña transition that was weaker than the large bloom previously observed during the 1998

El Niño/La Niña transition. The chl *a* bloom in the boreal spring of 2010 emerged in March and peaked in June, which was 1–2 months later than that in 1998 (initial increases in January and peak in May). Moreover, the bloom in 2010 was centered somewhat to the east of the 1998 bloom. No chl *a* bloom was observed during the 2007 El Niño/La Niña transition.

[19] The difference between chl *a* responses (in terms of magnitude and timing of the blooms) was attributed to the combined effect of two factors: the strength of the easterly trade winds during the transition to La Niña and the related island mass effect, and the preconditioning of the thermocline and mixed layer structure west of the Gilbert Islands by the preceding El Niño. The former enhances the vertical processes by shoaling the thermocline and EUC. The related upwelling and vertical mixing increase the supply of nutrients from the thermocline to the euphotic zone. The latter preconditions the depth of the thermocline and EUC as well as the thickness of the barrier layer, which affects the efficiency of the enhanced vertical processes before the transition to La Niña.

[20] Chl *a* is an indication of phytoplankton biomass (i.e., lowest trophic level in the food chain), such that changes in chl *a* can have an impact on higher trophic levels. To fully understand the possible impact of variations in El Niño/La Niña transitions on higher trophic levels in the western equatorial Pacific, changes in phytoplankton biodiversity, zooplankton biomass, and zooplankton biodiversity should be analyzed. Previous studies have suggested multidecadal change of El Niño characteristics in observations such as increasing amplitude of El Niño in the CP region over the past three decades [e.g., *Lee and McPhaden*, 2010] and more frequent occurrences of CP El Niño on multicentennial time scales in some climate models [e.g., *Yeh et al*., 2011]. Many climate models project to have less (more) frequent occurrences of EP (CP) El Niño under a global warming scenario [*Yeh et al*., 2009]. Therefore, our findings may have implications to the biological activities in the western Pacific on multidecadal time scales and in climate change scenarios.

[21] **Acknowledgments.** The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. M.M.G. was supported by the NASA New Investigator Program in Earth Science. K.B.K. was supported by NSF OCE 1031971.

[22] The Editor thanks one anonymous reviewer for his/her assistance in evaluating this paper.

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